LOW COST UPLINK CONCEPTS .

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Abstract

In order to minimize the cost of developing sequences of commands for small, low cost missions, a cost effective set of uplink tools used in conjunction with an appropriate ground system architecture (including a multi-mission operations facility) must bc utilized, This paper describes the steps in a generic uplink process that can bc used with a variety of ground system architectures. For each step, the multi-mission software tools that can bc used will bc described. These various tools already exist or arc under development and arc readily adaptable to a variety of distributed (e.g., remote science) architectures. In addition, various ways in which the uplink steps can bc physically distributed among a central multi-mission facility, the PI's home institution, and the spacecraft contractor's facility arc discussed. Features and rules of thumb of uplink systems that reduce costs arc described.

INTRODUCTION

Recent decisions by NASA make it clear that there will bc a trend toward lower cost unmanned planetary missions. In particular, the Discovery Program of $150M missions developed by a Principal Investigator, a NASA Center, and an industry partner is the motivation for the discussion that follows.

In the recent past, planetary missions have been very ambitious, costly enterprises characterized by large, complex spacecraft and instrument sets, and equally complex mission objectives and designs, Because they were flown relatively infrequently, the goal was to maximize performance. This resulted in pushing the margins (e.g., power margin) and packing in the maximum number of commands, thereby increasing operational complexity. In the future, it will bc imperative to lower operations costs. This means that tradeoffs will have to bc made that take into account the operations cost drivers: spacecraft operational complexity, instrument complexity, mission design complexity, packing of commands, and low margin philosophy. The first three of these drivers can bc addressed by actively using the method of concurrent engineering. This means that the operations system is engineered at the same time that the spacecraft, instruments, and mission design arc developed and that operability costs and complexity arc included in tradeoffs made with regard to these more traditional front end processes. That is to say, the life cycle cost is considered and operations is not left as an afterthought,

The effects of the last two, drivers can also bc mitigated by using a set of well engineered multi mission software tools such as the ones discussed below.

Other complications arc introduced by the desire to perform distributed operations (e.g., telescience). Performing operations in this way is feasible, but dots exacerbate communications problems among flight team members. In addition, if the distributed model is pushed too far, the multi-mission operations technology and expertise base that exists as a national repository at NASA centers such as JPL may be eroded, thus driving up the cost of future missions.[1] The pros and cons of various distributed architectures are discussed below. This paper concentrates on the uplink process (U/L) which is the most costly subset of flight operations. We begin with an overview of this process to provide a context for the discussion of architectures and tools.

OVERVIEW OF THE UPLINK PROCESS

The function of the Uplink Process is to transform user desires into spacecraft actions. User desires come in two flavors: science desires and supporting engineering desires. The supporting engineering desires have their basis in direct support of science observations and in maintaining the capability, health, and safety of the spacecraft and must be combined with the fundamental science desires to obtain an integrated sequence of commands that drives the actions of the spacecraft. The process that builds the sequence is composed of several steps: planning, generation, validation, translation, and commanding.

Sequence U/L planning consists of defining at the activity level the spacecraft and ground activities that are required to meet the mission requirements. Science, Engineering, and Mission Management are all involved in this activity. The process relies on insights into opportunities offered by flight and ground system capabilities and by geometric conditions. Various software tools are used to explore these opportunities and to aid in laying out an activity plan that does not violate high-level ground or spacecraft constraints intended to preserve resources or mission safety.

The generation process includes the design of the Science and Engineering activities contained in the activity plan. An example of a high-level science activity that might be developed at the command level in this process is the design of a Remote Sensing Mosaic. An engineering activity might be the command level design of a trajectory correction maneuver or of an engineering subsystem calibration or health check. This process utilizes software tools as well as human judgment.

The generation process also integrates the science and engineering activity designs and produces a sequence of time-tagged command mnemonics. Usually a number of automated constraint checks (pointing constraints, resource constraints, flight rules, mission rules) are performed as part of this process.

The validation process consists of further automated and human checks that ensure that the generated sequence is both safe and meets the intent of the requesters and designers. In some projects, a detailed hardware or bit level software simulation may be performed as the final fidelity check on the integrated sequence.

The translation step transforms the sequence of mnemonic commands into a bit level format suitable for transport to the commanding antenna and compatible with the spacecraft data system.

The commanding step transmits the sequence to the spacecraft during the proper commanding window and verifies that the commands have been properly stored on the spacecraft,

In the case of complex missions, this process is often not a simple single pass through the system, but requires multiple iterations. In a low cost mission, one should strive for a single pass by designing a robust (near constraint free) spacecraft and instruments. Remaining spacecraft constraints, mission rules, and flight rules should bc written in a way that they can bc automatically chcckcd by software. In this way, mission operations costs can bc significantly rcduccd.

UPLINK SEQUENCE TOOLS

Various existing and planned softwarc tools, based on years of cxpcricncc, arc available now or will bc available in the near future. All of these tools arc multi-mission. Some can bc used immediately, others require some lcvcl of mission-specific adaptation. The amount of adaptation nccdcd for any onc tool is dcpcndcnt on how much of its capabilities a project wishes to USC, Some provide generic capabilities applicable to all missions. Others support elaborate modeling of the spacecraft and ground systems. Most of the latter can bc adapted to provide minimal capabilities quickly, with additional capabilities added as the mission progresses and the need arises. This capability provides a low cost method of quickly producing an uplink systcm which captures many years of cxpcricncc in its structure. The following paragraphs provide brief discussions of component tools of this systcm.

System Control Tool

SUPAR provides an intelligent information backbone that allows multiple users, collocated or remote, to simultaneously access and manipulate planned scqucncc activities at any stage of the uplink process prior to uplink. It dccouplcs the input/output format dcpcndcncics that traditionally have existed by imposing a standard format and set of dcpcndcncy checks; thus, if a change in an activity or data set imposed by onc piccc of software requires another software set to bc rerun, SUPAR will either notify the user or automatically invoke the second software set.

Planning Tools

SOA (Scicncc Opportunity Analyzer) will process a set of spacecraft and planetary cphcmcridcs, and search for desired scicncc opportunities as defined by the user. Examples include: the time when a given phase angle occurs; the time when a given magnetic field value occurs; or the time when spacecraft occultation by a planet or ring occurs. The program will provide a rich visualization environment.

Plan -IT-II is an interactive planning tool that allows the user to view and manipulate a planned scqucncc of activities and supporting rcsourccs at multiple lcvcls of abstraction. The user may mouse-select any activity or rcsourcc for detailed information or for editing. With optional user supplied models, the program will identify conflicts bctwccn activities or rcsourccs in USC. Plan -l T-J] also has the capability, when invoked by the user, to automatically change the planned scqucncc to alleviate problems. This option requires user defined models of constraints and allowable changes.[2]

APGEN will bc the next generation of Plan-IT-II. It is used to plan the activities composing a mission at high-level. Activities can bc dcvclopcd and then either refined or abstracted as nccdcd, eventually yielding a baselinc scqucncc that can bc used as input to SEQ GEN. It supports prediction of rcsourcc usage by activities, as well as performing some hi~h-level constraint modeling. “Expert assistance” in developing and placing activities within a scqucncc is offered. Interaction with the user is accomplished through a graphical timclinc-typc intcrfacc.

Design and Generation Tools

SEQ_GEN is a scqucncc generation tool set that allows the user to crcatc and constraint check a series of spacecraft activities at the mnemonic command lcvcl. Spacecraft specific models of the spacecraft and ground systcm(s) to support functions such as automated state tracking, estimation of consumable usc, and checking of ground and spacecraft constraints can bc easily added or modified by the user. The core set of modules allows the user basic scqucncc editing capabilities, such as adding, modifying, deleting, and moving commands and spacecraft activities. It also provides time ordering of commands, accounting for onc-way and round trip light times, modclling of tracking station rise and set times, and an interactive graphical timclinc intcrfacc that allows the user to view and manipulate the scqucncc of activities. Discrctc commands can bc crcatcd and edited, and activities consisting of groups of commands can bc defined, Command macros that, with a fcw inputs from the user, expand into multiple commands arc also supported.[5]

SEQ_POINTER is used to interactively design passive remote sensing activities. The program allows the user to manipulate parameters of passive remote sensing observations, and scc the resulting instrument field-of views and mosaics projcctcd on a target body or, in the case of star fields, a rcfcrcncc sphere ccntcrcd on the spacecraft. By reading the spacecraft ephemeris (or modclling conic motion) and the planetary cphcmcris, and using data on relevant physical characteristics of the spacecraft and instrument, such as coordinate axes, instrument borcsight offsets, fields-of-view, allowable scan platform and/or mirror motion (if any), etc., the program accurately displays the observation design. The user can evaluate the design by using a variety of electronic projections and points-of-vicw; hardcopy output of the data, both graphical and tabular, is also available for analysis, Relevant (geometric and certain instrument operation) constraint checking is supported through user-supplied models. Activities dcvclopcd for SEQ_GEN can bc incorporated to ensure compatibility of both tools.[4]

TIMELINE gcncratcs a graphical rcprcscntation of a scqucncc of events on a printed page. The output is a visual map of a scqucncc at the event lcvcl, allowing the user to evaluate the temporal arrangement of activities and to rapidly locate a particular activity in relation to other activities. For example, onc can easily scc overlaps of spacecraft activities and the occurrence of spacecraft activities relative to tracking passes.[6]

Validation Tools

COMPARE gcncratcs a list of differences bctwccn two similar files. It is typically used to ensure that only desired changes were made to onc of the files, speeding the manual validation process. When used with multi-mission scqucncc files, it provides a smart comparison, compensating for lines and words that have been added or dclctcd.[6]

SEQ_REVIEW is a highly interactive tool that helps users validate a scqucncc by extracting" information from onc or two planned event files in accordance with a series of uscr-spccificd criteria. The user can strip a file of unwanted information, highlight records of interest, annotate records, reformat the file(s) into columns, and check for simple constraint conditions or violations based on user-dcvclopcd checks using a Little Language (resembling BASIC). Various tools, such as templates and visual programming aids, allow users access to most of this functionality without having to write software programs. The format of input files is not hard-coded into the program, but is dcscribcd in an external text file, These files can bc edited by the user to support non-standard formats, Spacecraft State Tracker (SST) is a set of tools designed to assist the analyst in determining the state of the spacecraft (either prcdictcd or, through tclcmctry, actual) at a particular time. In addition to rapidly generating prcdictcd state values, it provides filters and displays for analysis and reporting of state data. This scrutiny of state data is useful during the uplink and downlink phases of mission operations, It will allow the analyst to dctcrminc if the scqucncc of commands will accomplish the intended effect, evaluate prcdictcd subsystcm interaction and usc of rcsourccs, dctcrminc what needs to bc done to resolve identified problems, and compare the prcdictcd to the actual spacecraft state.

SEG is a reformatting program that uscs the output of SEQ_GEN to produce a compendium of planned activities at the command lcvcl in an cfficicnt format. It offers a choice of graphical or tabular formats that can bc modified by a particular project, and presents the information in a manner that has been refined and found over the years to bc cffcctivc for review and realtime monitoring operations.[7,8]

HSS (I{igh-Speed Simulator) provides a project with a means of rapid validation of a planned scqucncc by duplicating the activities of a spacecraft through a bit lcvcl simulation of its data systems, HSS loads the flight software, spacecraft state, and memory loads gcncratcd by SEQTRAN to initialize the simulator. The simulator then models the scqucncc by executing the flight software scqucncc memory loads, and gcncratcs a set of prcdictcd events. Both the uplink and downlink interfaces can bc simulated in this manncr[9,10,11,12]

Translation Tool

SEQTRAN (scqucncc translator) is a macro processor, asscmblcr, and loader that converts SEQ_GEN output (command mnemonics and memory loads) into a binary format compatible with transport by the ground data systcm for radiation to the spacecraft and processing by the spacecraft command subsystcm. The program can bc used for processing of both realtime and stored commands, and can provide management of the on board memory by tracking memory usc and ensuring pending commands arc not overwritten. The commands and memory loads can bc dircctcd to the central spacecraft processor or subsystcm processors, including instruments.

MOS ARCHITECTURES

The traditional way in which planetary missions have been flown was to collocate the mission operations support personnel. Typically, the personnel would bc collocated within the same building. This architecture enabled face-tc)-face communication bctwccn operations personnel. In today's environment with cnhanccd communications abilities, it is no longer mandatory to collocate all operations personnel. Operations can bc accomplished with operations personnel located across the country (or around the world), albeit with some loss of efficiency. in particular, "tclcscicncc" can be performed with such a systcm. The following sections dcscribc the various uplink related, functions and how these could bc physically distributed in a mission operations cnvironmcnt. The advantages and disadvantages of each arc discussed.

For this discussion, three physical sites where the U/L functions could bc located were considered. They arc 1) Jet Propulsion Laboratory, 2) the PI's home institution, and 3) the S/C contractor's facility.

JPL, located in Pasadena, California, has a vast amount of multi-mission facilities, S/W tools and expertise that can be used to support Mission Operations.

The science site would be located at the Pi's home institution or at a facility nearby. This would enable the PI to continue with his research while simultaneously performing some subset of mission operations functions.

The third physical site would be located at the S/C Contractor's facility. Doing some U/L functions here would enable part time support from the S/C contractor since the support personnel could continue with other tasks at the facility. This would allow experts to participate directly in anomaly resolution and other activities where very detailed knowledge of the S/C is required,

With five different functions and three possible locations, there are approximately 250 different ways to distribute the functions. Most of these would be inherently inefficient; for example, locating the Science Operations at the S/C Contractor's facility and the Engineering Operations at the PI's home institution. Discussed below are the four basic options that take advantage of each location's inherent strengths. The first option is the traditional one, all functions at a central location. The next three variously distribute the functions to the P1's Home Institution and the S/C Contractor's Facility, as well as JPL. All options assume that Navigation, Commanding, and Tracking (via the Deep Space Network) are done at JPL. In this discussion, the terms "science operations" and "engineering operations" refer to that portion of the design and validation steps performed by science and engineering.

Architecture 1 - Traditional

in this architecture, all major functions are done at a central location where multi-mission facilities and expertise exist. This means that sequence planning, sequence generation, validation, translation, and commanding would be done at the central site, Science operations personnel would be trained or imported to do the science operations and S/C experts would be trained or imported from the S/C contractor to do the Engineering 'operations. For example, recent flight experience utilizing this method at JPL has shown it to be effective.

This option has the advantage of not having to develop new operations facilities or new U/L software tools while being able to utilize the existing multi-mission operations expertise. Excellent interpersonal communications are enabled. Meetings can be held where the other members of the operations team are right across the table and without having to deal with across time zone scheduling problems. Also, with this option, a multi-mission base of experience and facilities is maintained for future missions. This is very important if future missions are to be operated at low cost.

On the down side, it requires that some Science and S/C support personnel to move to this location. This may require the relocation of personnel (and their families) for an extended period of time. This is an expense that a small Discovery mission may not be able to afford. One way to minimize the cost of re-locating the S/C operations personnel is to operate the S/C with people that are not S/C experts (i.e., generalists or systems personnel), This will minimize the number of S/C operations personnel relocated and may enable personnel from the central site to be trained to operate the S/C. The only time S/C contractor personnel would be required would be through the launch phase and for anomaly investigation, This approach was used for the TOPEX mission. During launch and the two-month assessment phase of the mission, some S/C contractor personnel (those with kcy S/C cxpcrtisc) were located at the central site. After that, all but a fcw of the spacecraft contractors returned to their home site and the mission operations were performed by pcoplc with lcss detailed S/C knowledge. The experts were then "on call" to assist in any anomalies.

The generalist concept would bc difficult to utilize if the S/C were not designed in the first place to bc flown by generalists. In the past, the S/C was designed and built before the operations personnel joined the project. When S/C design problcms/options were encountcred, there was little incentive to decide in favor of operability. Onc concept that is a must for the Discovery class missions is that of concurrent cnginccring. The S/C and Ground System must bc designed and built simultaneously. This will allow the systcm to bc dcvclopcd as a whole, When tradeoffs must bc made, long-term operations impacts can bc balanced against short term S/C dcvclopmcnt costs. With this approach, a S/C design that is easy to operate bccorncs more likely. This approach is currently bc used by the Mars Pathfinder Project. Both the S/C and ground systems arc being dcvclopcd simultaneously with sornc S/C and ground systcm dcvclopmcnt personnel being collocated together.

Architccturc 2- Remote Scicncc

This architecture has all functions at a central multi-mission site cxccpt for the Scicncc Operations which would bc at the PI's home institution. This means that the detailed scicncc activity designs and U/l. product reviews would bc done at the PI's home institution while the scqucncc planning, engineering operations, scqucncc generation, validation, translation, and commanding would bc done at the central site.

This will enable science personnel to "stay at home" which will minimize travel and relocation costs. Also, the scicncc operations costs could bc lowcrcd since graduate students could bc utilized to perform some functions. This option has the advantage of not having to develop a major portion of an operations facility and would allow the usc of operations cxpcrtisc that exists at a multi-mission facility. Interpersonal communications arc cnhanccd for cvcryonc cxccpt bctwccn the central site and the science operations personnel. With a good inter-facility communication ability, this negative can bc minimized. Also, with this option, a multi-mission base of cxpcricncc and facilities is maintained for future missions.

The disadvantages for this option arc similar to architecture 1. Spacecraft operations personnel will have to bc imported. Also, bccausc of the remote scicncc operations personnel, the interaction with the central site for conflict/priority resolution cannot bc done face to face. Given possible time zone diffcrcnccs, it could bc difficult to get quick resolution of such issues. Interactions with scicncc can bc minimized if the instrument is designed with remote scicncc operations in mind. This brings up a prcvious concept, concurrent cnginccring. The instrument and its ground operations systcm must be designed so as to allow remote scicncc. An instrument that requires constant attention, or has many operational constraints, will bc more difficult and more costly to operate. The last disadvantagc is that the project specific remote scicncc facility has to bc dcvclopcd. Some home institutions may already have facilities in place, but most will not,

Architccturc 3 - Remote Scicncc & Engineering

In this architccturc, the multi-mission site is still used, but both scicncc and cnginccring operations arc done at their rcspcctivc facilities, The scicncc operations would be done at the PI's home institution and the cnginccring operations at the S/C contractor's facility. This means that the detailed activity designs and U/l, product reviews would bc done at the

Pi's home institution and the S/C contractor's facility while continuing to do the Sequence Planning, Sequence Generation, Validation, and Translation of the Science and Engineering Sequences, final constraint checking, and Mission Commanding at the central site. This will enable science and engineering personnel to "stay at home," which will minimize travel and relocation costs. This option has the advantage of utilizing a multi-mission facility and U/L software tools with multi-mission operations expertise. Also, with this option, a (reduced) multi-mission base of experience and facilities is again maintained for future missions.

The disadvantages for this architecture are the difficulties inherent with any remote operations. Interpersonal communication will not be as good as it would be for a collocated flight team. The interaction with the central site for conflict/priority resolution cannot be done face to face. Time zone differences will again present a problem to quick resolution, Another disadvantage is that project specific science and engineering operations facilities will have to be developed. Some facilities may already be in place, but in many cases, they will have to be developed.

Architecture 4- PI Centered

This architecture has all U/L functions **being done** at the PI's home institution except for Mission Commanding which would still be done at a multi-mission operations site, This option has enhanced interpersonal communication since the functions that normally require conflict/priority resolution are collocated at the PI's facility. Travel/relocation costs would only be incurred for the S/C operations personnel.

The significant disadvantage for this option is that an operations facility, including operations personnel, must be developed at the PI's home institution. Also, engineering operations personnel must be imported from the S/C contractor. Costs associated with this could be very large when compared to the cost of using an existing multi-mission operations site staffed with multi-mission operations personnel. A competent operations team will have to be developed from scratch and the development of such a mission operations capability would only be used for a single mission, There would be very limited, if any, carryover of facilities or personnel to other missions. The final disadvantage concerns the long-term maintenance of a national multi-mission operations facility. If such a facility is not utilized, it will be very difficult to maintain that capability for future flights. Similarly, mission operations and sequence implementation will not have a multi-mission software and experience base to form a foundation that allows future missions to develop low cost, derivative uplink systems.

CONCLUSIONS

Concurrent engineering of the mission design and the spacecraft, instruments, and ground systems is very important to producing an efficient, low-cost operations environment. In this way, a robust, operable spacecraft can be produced. This minimizes the amount of constraint checking that must be done and **the** number of iterations in the U/L process. Most of the planning, generation, and validation can then be accomplished via efficient modern multi-mission software tools.

The choice of the right architecture for distributed operations, over a series of low-cost missions that have different PIs and spacecraft manufacturers, is important for maintaining a repository of tools and expertise that will minimize cost and enhance performance over an ensemble of future planetary missions. The architecture most likely to accomplish this is the remote science option.

With the selection of properly designed missions, concurrently engineered spacecraft and ground systems, properly selected ground system architectures, and innovatively designed tools, the nation can look forward to an era of productive, low cost planetary missions.

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